MODELING THE FAILURE AND FLOW OF ANISOTROPIC CRACKED SEA ICE

Prof. W.D. Hibler III
Thayer School of Engineering
Dartmouth College
Cummings 8000
Hanover, NH 03755
billh@dartmouth.edu
Tel.: 603-646-3172, FAX: 603-646-3856
Award No. N00014-97-1-0381

LONG TERM GOALS

Develop a physically based model for predicting leads and oriented flaws in sea ice and their resulting deformation characteristics.

OBJECTIVE

A conceptual notion here is that leads in a pack ice cover develop from the interaction and propagation of existing oriented leads and flaws. To develop a model for this we have focused on modeling the failure and interaction of oriented flaws and how this interaction affects both the weakening of existing flaws and propagation of damage.

APPROACH

To this end we have developed and numerically investigated the interaction of oriented anisotropic elements in pack ice and examined how this interaction affects the near field stress and failure on individual oriented anisotropic elements. For this purpose a local anisotropic model developed by Hibler and Schulson (1997) in FY 97 was modified to include a more realistic treatment of the thin ice so that its failure characteristics follow a yield curve close to that observed in the laboratory for biaxial failure of columnar sea ice. The basic idea in the anisotropic representation is to take one or more oriented weak leads imbedded in stronger sea ice, as illustrated by Figure 1. Consistent with continuum mechanics we take the stress to be continuous at the thin ice/thick ice interface which implies that σ_{11} and σ_{12} are continuous. If we further assume that the strain rate components in the thin and thick ice have a real weighted sums equal to the composite values, and assume viscous plastic constitutive laws for both the thin and thick ice, anisotropic characteristics for the composite may be obtained by solving a set of four nonlinear equations. The resulting failure and flow characteristics of the composite can then be used in a full boundary value solution of spatially separated interacting flaws. The failure and propagation characteristics of both the flaws and the composite were then methodically numerically investigated and examined in light of observational and laboratory experiments.

ACCOMPLISHMENTS

In order to examine the local failure characteristics of a series of oriented flaws imbedded in stronger ice, a series of numerical experiments were carried out to determine what oriented leads are most likely to fail and what the flow characteristics of the composite are. To examine imbedded flaws interacting with spatially separated flaws in other regions a numerical framework for the anisotropic boundary value problem was constructed based on the local failure characteristics. A series of simulations were then carried out to determine how the interaction

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **Modeling the Failure and Flow of Anisotropic Cracked Sea Ice**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dartmouth College,Thayer School of Engineering,Hanover,NH,03755**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

between flaws caused a modification of the far field stress in the vicinity of the flaw; what the aggregate failure characteristics were, and under what conditions local flaws were weakening. The damage propagation characteristics were examined by slowly increasing the external stresses until plastic damage originating with the flaws propagated through the whole system.

In addition to these efforts, to understand how leads open up in floating pack ice after a failure pattern has formed, a numerical framework for investigating coupling between inertial oscillations and kinematic waves was developed.

SCIENTIFIC RESULTS

Numerical investigation of the local anisotropic failure characteristics of a flaw imbedded in thick ice showed that there is a preferred orientation for failure with the orientation of the flaw depending on the degree of confinement (Figure 2). With low confinements the flaw intersection angle relative to the applied stress is very small and will asymptotically approach zero as the confinement goes to zero. For confinement up to about 0.25 the weakest oriented lead will open; beyond 0.25 it will close and ridge. Beyond a critical confinement of about .3 the most likely failing lead occurs perpendicular to the largest compressive stress direction where it remains for all higher confinement ratios.

With regard to flow characteristics, the failure of the flaw takes place with the stress principal axes tending to be more closely oriented with the lead orientation than the principal axes of the strain rate except at very low confinement. This reflects the basic anisotropic failure characteristics where the principal axes of the stress and strain are not aligned. Opening rates of the leads were found to be very large for leads highly aligned with the principal axes of stress.

For interacting spatially separated imbedded flaws, a full anisotropic boundary value solution showed that there is a strong modification of the local near field stress by the anisotropic response of the oriented element with the local principal axis more closely aligning with the orientation of the flaw. Because of the stress shedding effect it is found that for a wide range of confinement ratios, only flaws in a narrow range of angles of ~10-20° relative to the far field stress are found to both fail and open so that they become weaker. This supplies one explanation of why intersecting leads are often observed at 30°. An example of activated flaws being “picked out” by the far field stress is shown in Figure 3. A critical point here is that while all the flaws are failing, only certain flaws both fail and weaken.

With respect to damage propagation, the propagation of plastic failure proceeds in a complementary intersecting direction relative to the applied stresses. This damage propagation direction more closely aligns with the principal stresses when the “activated” leads are made weaker leading to an approximate 30° intersection angle between damage strikes. These results are in general agreement with laboratory experiments (see Schulson progress report) which show that failure of precracked ice is largely controlled by the orientation and character of the existing flaws.

Overall these results present a coherent picture (Hibler and Schulson, submitted for publication) of how leads and ridges arise out of a region containing a variety of interacting flaws with differing strengths and orientations. Certain flaws fail, form ridges and hence strengthen. This process continues until flows more closely aligned with the principal far field stress fail and open, hence weakening. This weakening then leads to damage propagation through the matrix of ice floes and different ice strengths. Differential drift along these damage patterns can couple with inertial oscillations leading to fluctuating deformation (Hibler and others, in press) which can be manifested by opening and closing of leads.

To fully simulate this phenomenon requires incorporation into this model of the weakening and strengthening of leads and determination of the local anistropic response of a variety of oriented leads of different weaknesses.

IMPACT FOR SCIENCE AND SYSTEMS APPLICATIONS

This work is directly relevant to ice forecasting models for both Naval operations and sea ice dynamics models for climate oriented studies. It is a step forward for developing a sea ice dynamics model allowing the forecasting of oriented leads. This work has Scientific applications in that it also supplies a different theoretical model for examining fracture and flow incorporating plastic failure in smaller scale experimental studies.

TRANSITIONS

The main transition of this work is to incorporate aspects of this fracture based failure into sea ice forecast models. This will likely occur in some form during the next fiscal year.

RELATED PROJECTS

This study is closely related to a concurrent investigation on the laboratory mechanics of flawed sea ice by Prof. Erland Schulson. (The flow and fracture of cracked ice: experiments to aid modeling.) One paper on this subject is in press and another largely covering the results described in this progress report has been submitted for publication.

REFERENCES

Hibler, W.D., III and E.M. Schulson, 1997: On modeling sea ice fracture and flow in numerical investigations of climate, *Annals of Glaciology,* 25, in press.

Hibler, W.D., III and E.M. Schulson, 1998: On modeling the anisotropic failure and deformation of flawed sea ice, submitted for publication.

Hibler, W.D., III, P. Heil, and V. Lytle, 1998: On simulating high frequency variability in Antarctic sea-ice dynamics models, *Annals of Glaciology*, **27**, in press.

PUBLICATIONS

Zhang, J. and W. D. Hibler III (1997), On an efficient numerical method for modeling sea ice dynamics, *J. Geophys. Research*, 102, 8691-8702.

Hibler W.D., III, and E.M. Schulson, 1997: On modeling sea ice fracture and flow in numerical investigations of climate, *Annals of Glaciol.*, 25, in press.

Zhang, J., W.D. Hibler, III, M. Steele, and D.A. Rothrock, 1997: Arctic ice-ocean modeling with and without climate restoring, *J. Phys. Oceanogr.*, in press.

Geiger, C.A., W.D, Hibler, III and S.F. Ackley, 1997: Large -scale sea ice drift and deformation: Comparison between models and observations in the Western Weddell Sea during 1992, *J. Geophys. Res.*, in press.

Hibler, W.D., III, P. Heil and V.I. Lytle, 1998: On simulating high frequency variability in Antarctic sea-ice dynamics models, *Annals of Glaciology*, 27, in press.

Hibler, W.D., III and E.M. Schulson, 1998: On modeling the anisotropic failure and flow of flowed sea ice, submitted for publication.

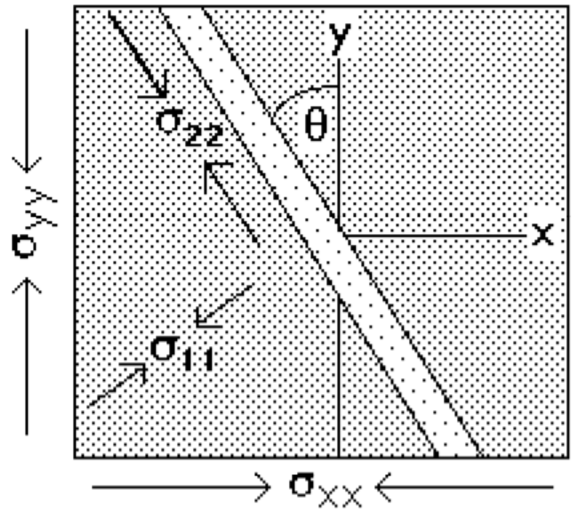

Figure 1. Schematic of oriented weak flaw or lead imbedded in stronger ice.

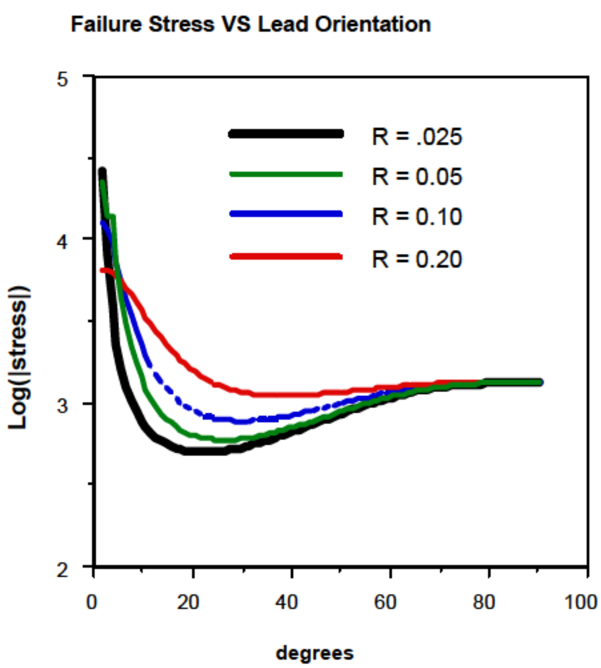

Figure 2. Failure stress σ_{yy} versus angle θ in degrees for different confinement ratios R = σ_{xx}/σ_{yy}.

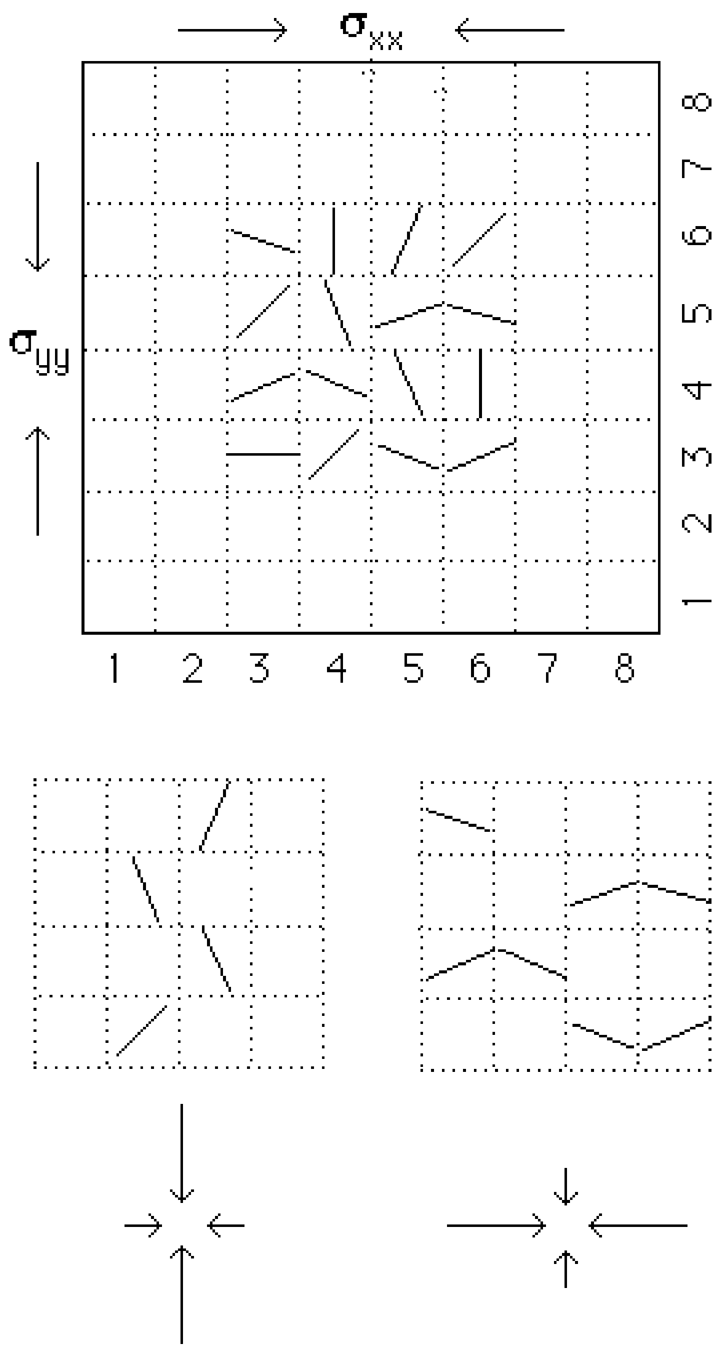

Figure 3. Schematic of random oriented flaws together with"activated" flaws for differently oriented maximum principal stresses.